# A Survey of Radioactivity Produced by High Energy Neutron Bombardment

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A large number of the known stable elements have been bombarded by neutrons of energies ranging up to 20 Mev. The transmutation reaction of the type involving the ejection of two neutrons is apparently evident with varying degrees of intensity in nearly all the elements of the periodic table. In addition, reactions of the type where a proton or an alpha-particle is ejected are observed. For bombarding neutrons of low energy these reactions are observed only for relatively light elements, but for very energetic neutrons such reactions are evidently quite common in elements of high atomic number.

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Table I. *Radioactivity produced by very high energy neutron bombardment.*

| At. No. | Element bombarded | Period, intensity, sign, assignment | Other work |
|---|---|---|---|
| 6 | C | 20 m, *vw*, +, $C^{11}$ | |
| 7 | N | 10.5 m, *vw*, +, $N^{13}$ | |
| 8 | O | 2.1 m, *vw*, +, $O^{15}$ | 2.1 m[1] |
| 9 | F | 108 m, *w*, +, $F^{18}$ Chem. | |
| 12 | Mg | 15 h, *vs*, −, $Na^{24}$ | |
| 13 | Al | 10 m, *vs*, −, $Mg^{12}$ | |
| | | 15 h, *vs*, −, $Na^{24}$ Chem. | |
| 14 | Si | 6 m, *vw*, +, $Si^{27}$ | |
| | | 11 m, *vw*, +, | |
| 15 | P | 3 m, *vs*, +, $P^{30}$ | 2.5 m[2] |
| | | 2.5 h, *s*, −, $Si^{31}$ | |
| 16 | S | 26 m, *vw*, +, $S^{31}$ | |
| | | 14 d, *s*, −, $P^{32}$ | |
| 17 | Cl | 33 m, *vs*, +, $Cl^{34}$ Chem. | |
| | | 14 d, *s*, −, $P^{32}$ | |
| 19 | K | 7.5 m, *s*, +, $K^{38}$ | |
| | | 4 m, *s*, −, | |
| | | 1.8 h, *w*, −, $A^{41}$ | |
| 20 | Ca | 4.5 m, *vw*, +, $Ca^{39}$ | |
| 21 | Sc | 4 h, *vs*, +, $Sc^{43}$ | |
| | | 2 d, *s*, +, $Sc^{44}$ | |
| 22 | Ti | 1.7 h, *vs*, −, Sc | |
| | | 28 h, *s*, −, Sc | |
| 23 | V | 4 m, *s*, −, $V^{52}$ Chem. | |
| | | 1.8 d, *vw*, | |
| 24 | Cr | 4 m, *vs*, −, $V^{52}$ | |
| | | 1.7 h, *s*, −, | |
| 25 | Mn | 3.6 m, *vs*, −, V | |
| | | 2.5 h, *s*, −, $Mn^{56}$ | |
| 26 | Fe | 2.5 h, *vs*, −, $Mn^{56}$ | |
| 27 | Co | 2.5 h, *s*, −, $Mn^{56}$ Chem. | 11 m[3] |
| 28 | Ni | 2 h, *w*, | 2.7 h[3] |
| | | 6 d, *vw*, | 11 m[3] |
| 29 | Cu | 10 m, *vs*, −, $Cu^{62}$ | 10.5 m[2, 4, 3, 1] |
| | | 12.5 d, *vs*, ±, $Cu^{64}$ Chem. | |
| 30 | Zn | 6 m, *vs*, −, $Cu^{66}$ | 6 m[4] |
| | | 40 m, *vs*, +, Zn Chem. | 38 m[2], 60 m[4, 3] |
| | | 12.5 h, *vs*, ±, $Cu^{64}$ Chem. | |
| 31 | Ga | 20 m, *vs*, −, $Ga^{70}$ | 20 m[2], 5 m[1] |
| | | 55 m, *vs*, +, $Ga^{68}$ Chem. | 60 m[1] |
| | | 1.7 h, *s*, +, | |
| | | 22 h, *w*, −, $Ga^{72}$ | |
| 32 | Ge | 1.3 h, *s*, −, | |
| | | 20 h, *w*, −, $Ge^{72}$ | |
| 33 | As | 1.1 d, *vs*, −, $As^{76}$ Chem. | |
| | | 13 d, *w*, | |
| 34 | Se | 1 h, *vs*, −, Se Chem. | 56 m[4] |
| 35 | Br | 7 m, *vs*, , $Br^{78}$ | 3.5 m[2], 5 m[4] |
| | | 18 m, *vs*, , $Br^{80}$ Chem. | 18 m[4, 2, 5] |
| | | 4 h, *s*, , $Br^{80}$·Chem. | 5 h[1], 24 h[5] |
| 37 | Rb | 11 m, *vs*, −, | |
| | | 22 h, *s*, −, | |
| 38 | Sr | 18 m, *s*, −, | |
| | | 3 h, *s*, +, Sr Chem. | |
| 39 | Y | 11 m, *s*, −, | |
| | | 1.2 h, *s*, | |
| | | 6.5 h, *w*, −, | |
| | | 2.4 d, *vw*, −, $Y^{90}$ | |
| 40 | Zr | 10 m, *s*, | |
| | | 5 h, *w*, , Zr | |
| | | 44 h, *w*, , Zr | |
| 41 | Cb | 7.3 m, *w*, | |
| | | 3.8 d, *w*, | |
| 42 | Mo | 17 m, *s*, −, | 21 m[4], 17 m[2] |
| | | 5 d, *w*, −, | |
| 44 | Ru | 24 m, *w*, | |
| | | 3.6 h, *w*, | |
| 45 | Rh | 4 m, *s*, −, | |
| | | 1.1 h, *w*, −, | |
| 46 | Pd | 18 m, *w*, −, Pd | |
| | | 12.5 h, *w*, −, Pd | |
| 47 | Ag | 25.5 m, *vs*, +, $Ag^{106}$ Chem. | 24 m[4, 2, 1] |
| | | 13 d, *w*, −, Ag Chem. | |
| 48 | Cd | 33 m, *s*, +, | |
| | | 3 h, *w*, −, $Cd^{115}$ | 3.3 h[4] |
| | | 53 h, *vw*, −, $Cd^{117}$ | |
| 49 | In | 1.1 m, *s*, −, | 1 m[2, 1] |
| | | 54 m, *s*, −, In Chem. | |
| | | 4 h, *vs*, −, In Chem. | |
| | | 2 mo, *s*, −, In Chem. | |
| 50 | Sn | 47 m, *s*, −, | |
| 51 | Sb | 15.4 m, *s*, +, $Sb^{120}$ | 13 m[2, 1] 17 m[4] |
| | | 2.3 d, *w*, −, $Sb^{122}$ | |
| 52 | Te | 1.1 h, *vs*, −, | 60 m[4, 2] |
| | | 30 d, *w*, | |
| 53 | I | 26 m, *s*, , $I^{128}$ Chem. | |
| 56 | Ba | 2.5 m, *s*, | |
| | | 85 m, *w*, , $Ba^{139}$ | |
| 57 | La | 2.2 h, *w*, | |
| 58 | Ce | 40 m, *w*, −, | |
| 59 | Pr | 3 m, *w*, +, $Pr^{140}$ | |
| | | 20 h, *w*, , $Pr^{142}$ | |
| 60 | Nd | 2.2 h, *w*, −, | |
| | | 19 h, *w*, −, $Pr^{142}$ | |
| 64 | Gd | 19 h, *w*, −, | |
| 66 | Dy | 2.5 h, *w*, −, | |
| 73 | Ta | 9.1 h, *w*, | 14 m[2] |
| 75 | Re | 18 h, *s*, −, $Re^{186}$ | |
| 77 | Ir | 15 h, *s*, −, $Ir^{192}$ | |
| 78 | Pt | 1.8 h, *s*, −, | |
| | | 3 d, *vw*, | |
| 79 | Au | 17 m, *w*, | |
| | | 2.5 d, *w*, , $Au^{198}$ | |
| 80 | Hg | 45 m, *s*, −, | 43 m[4] |
| 81 | Tl | 5 m, *s*, , $Tl^{206}$ | 4.1 m[4] |
| | | 50 m, *vw*, , $Tl^{204}$ | |
| 82 | Pb | 5 m, *w*, −, | |
| | | 1.5 h, *w*, −, | |
| 90 | Th | 5 m, *vs*, −, | |
| | | 1.4 h, *s*, | |
| 92 | U | 26 m, *vs*, −, | |
| | | 4 h, *s*, −, | |
| | | 13 h, *s*, −, Eka Os | |

[1] Chang, Goldhaber and Sagane, Nature **138**, 962 (1937).
[2] Bothe and Gentner, Naturwiss. **25**, 90, 126, 191 (1937).
[3] Heyn, Physica **4**, 160 (1937).
[4] Heyn, Nature **138**, 723, 842 (1937).
[5] Johnson and Hamblin, Nature **138**, 504 (1936).

These neutrons of high energy are obtained by the previously reported method of bombarding lithium in the cyclotron with 6.3 Mev deuterons.[1]

The results are summarized in Table I. The assignment of the periods is tentative and is based upon evidence from the sign of the emitted beta-particle, the chemical separations and known periods from other sources. Detailed work is necessary in many cases to make identification positive. Of the 113 periods listed in the table only about a fourth can also be obtained by slow neutron bombardment. Bismuth was the only element tried that gave no measurable radioactivity.

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[1] Pool, Cork and Thornton, Phys. Rev. **51**, 890 (1937).